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A STUDY ON COST OPTIMIZATION OF INTERNAL CYLINDRICAL GRINDING

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ABSTRACT

This study aims to minimize the grinding cost of internal cylindrical grinding of stainless steel 316 using optimal exchanged grinding wheel diameter. The relationships of the grinding cost, the exchanged grinding wheel diameter and the grinding process parameters are calculated by mathematical functions. The influences of ten grinding process parameters including the initial grinding wheel diameter, the width of grinding wheel, the total depth of dressing cut, the tolerance grade, the grinding wheel life, the radial grinding wheel wear per dress, the machine tool hourly rate, the wages including overhead cost, the grinding wheel cost, and the ratio of workpiece length per workpiece diameter on the exchanged grinding wheel diameter have been investigated. Based on 128 sets of the grinding parameters, the optimum exchanged grinding wheel diameter related to the minimal grinding cost have been determined as a function of the grinding parameters. This developed relation can be further applied for cylindrical internal grinding to reduce the grinding cost.

Keywords: Grinding, Internal Grinding, Cost Optimization, Optimum Exchanged Diameter.

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1. INTRODUCTION

Grinding process is commonly used to achieve the quality of a surface finish [1-2]. The main objectives of grinding process are to reduce surface roughness, increase manufacturing accuracy as well as material removal rate [1-2]. Therefore, numerous studies have concentrated on optimizing grinding process parameters i.e. cutting parameters, dressing parameters and coolant parameters to obtain those objectives [1-10]. In comparison with other grinding processes, internal cylindrical grinding process is more complex because of the limitation of manufacturing space especially workpieces with small and long holes [3-4]. In these cases, several grinding parameters are efficiently adjusted to meet technical requirements, however, this change but may increase grinding expense and the total price of finished products. Thus, the minimization of grinding cost is necessary along with keeping surface quality up. This problem has been mentioned in a number of studies to reduce grinding time, increase grinding wheel life, and minimize quantity lubrication [5-16]. In some recent studies, cost optimization in both external and internal grinding processes are minimized with optimum exchanged grinding wheel diameter [17-21]. This optimum exchanged grinding wheel diameter is obtained by investigating the effects of grinding process parameters such as the initial grinding wheel diameter, the total dressing depth, the radial grinding wheel wear per dress, and the wheel life. However, numerous grinding parameters that may have influence on optimum exchanged grinding wheel diameter have not been studied yet. Therefore, in this study, more internal grinding process parameters are considered to understand their effects on the optimum exchanged grinding wheel diameter as well as the minimum grinding cost. In this study, the relation of the grinding cost, the exchanged grinding wheel diameter and the grinding process parameters are presented in mathematical functions [21-22]. Thus, the influences of the grinding process parameters on the exchanged grinding wheel diameter can be calculated. Ten internal cylindrical grinding process parameters i.e. the initial grinding wheel diameter, the width of grinding wheel, the total depth of dressing cut, the tolerance grade, the grinding wheel life, the radial grinding wheel wear per dress, the machine tool hourly rate, the wages including overhead cost, the grinding wheel cost, and the ratio of workpiece length per workpiece diameter are chosenfor study. These two-level parameters are set up in 128 designed experiments for stainless steel 316 [23]. The optimum exchanged grinding wheel diameters are determined after calculating the grinding wheel diameter. Based on the calculated results, the influences of grinding parameters are evaluated and the function of optimal exchanged grinding wheel diameter is established. This relation of optimal exchanged grinding wheel diameter and grinding parameters can be used to conduct the real grinding experiments.

2. GRINDING COST FUNCTION

In internal grinding process, the manufacturing single cost per piece $C_{\sin}$ ***can be determined as follows:***

$$C_{\sin} = \left(C_{mh} + C_{wh}\right) \cdot t_s + C_{gw,p} \quad (1)$$

Wherein,

C_{mh} is the machine tool hourly rate (USD/h);

C_{wh} is the wages including overhead cost;

$C_{gw,p}$ is the grinding wheel cost per part (USD/part) and is calculated by:

$$C_{gw,p} = C_{gw} / n_{p,w} \tag{2}$$

where, C_{gw} is the cost of an internal grinding wheel (USD/piece); $n_{p,w}$ is the total number of parts ground by a grinding wheel and it can be written as[1]:

$$n_{p,w} = \left(d_{s,0} - d_{s,e}\right) \cdot n_{p,d} / \left[2\left(\delta_{rs} + a_{ed,ges}\right)\right] \tag{3}$$

In which, $d_{s,0}$ is the initial grinding wheel diameter (mm); $d_{s,e}$ is the exchanged grinding wheel diameter (mm); δ_{rs} is the radial grinding wheel wear per dress (mm/dress); $a_{ed,ges}$ is the total depth of dressing cut (mm); $n_{p,d}$ is the number of parts per dress and is given by:

$$n_{p,d} = t_w / t_c \tag{4}$$

where, t_w is the wheel life (h) and t_c is the grinding time (h),

$$t_c = l_w \cdot a_{e,tot} / \left(v_{fa} \cdot f_r\right) \tag{5}$$

In which, $a_{e,tot}$ is the total depth of cut (mm), l_w is the length of part (mm), v_{fa} is the axial feed speed (mm/min) and f_r is the radial wheel feed (mm/double stroke).

The axial feed speed v_{fa} is calculated by [21]: $v_{fa} = 22.88 \cdot D_{gw}^{0.9865} \cdot d_w^{0.0821} \cdot tg^{-2.9833} \cdot n_w^{1.2471}$ (for stainless steel 316).

In the above formulas, D_{gw} is the grinding wheel diameter; d_w is the workpiece diameter; tg is the tolerance grade; n_w is the workpiece speed; From the tabulated data in [22], n_w can be determined by the following regression model [21]: $n_w = 1255.8 \cdot d_w^{-0.3491}$ (for stainless steel 316).

f_r is the radial wheel feed (mm/double stroke); f_r is determined by [21]:

$$f_r = f_{r,tab} \cdot c_1 \cdot c_2 \cdot c_3 \cdot c_4 \tag{6}$$

where, $f_{r,tab}$ is the tabled radial wheel feed (mm/double stroke); From the tabulated data in [22], the following regression equation was found for determining $f_{r,tab}$ [21]:

$$f_{r,tab} = 30.2944 \cdot a_{e,tot}^{0.567} \cdot v_{fa}^{-0.9693} \cdot d_w^{-0.1269} \tag{7}$$

Wherein, $a_{e,tot}$ is the total depth of cut (mm).

c_1 is the coefficient which depends on workpiece material and tolerance grade tg; c_1 is calculated by [21] (for stainless steel 316): $c_1 = 0.0857 \cdot tg^{1.2767}$;

c_2 is the coefficient which depends on grinding wheel diameter d_s. Based on data in [22], c_2 can be calculated by the following regression equation (with $R^2 = 0.9977$):

$$c_2 = 0.5657 \cdot d_s^{0.153} \quad (8)$$

c_3 is the coefficient which depends on measurement type; $c_3 = 1$ if a micrometer is used for measurement and $c_3 = 1.4$ if a snap gauge is used [22];

c_4 is the coefficient which depends on the character of workpiece's hole and the ratio of the length of workpiece (l_w) to its diameter (d_w). Based on the data in [22], $c_4 = 1.0642 \cdot (l_w / d_w)^{-0.5079}$ when grinding continuous cylindrical hole (with $R^2 = 0.9637$); $c_4 = 1.375 \cdot (l_w / d_w)^{-0.5058}$ when grinding non-continuous cylindrical hole (with $R^2 = 0.955$); $c_4 = 0.8514 \cdot (l_w / d_w)^{-0.5079}$ when grinding cylindrical hole with a curved shoulder (with $R^2 = 0.9637$);

t_s is the manufacturing time includes auxiliary time (h); in internal grinding process, the manufacturing time can be expressed as:

$$t_s = t_c + t_{lu} + t_{sp} + t_{d,p} + t_{cw,p} \quad (9)$$

where, t_{lu} is the time for loading and unloading workpiece (h); t_{sp} - spark-out time (h); $t_{d,p}$ - dressing time per piece (h):

$$t_{d,p} = t_d / n_{p,d} \quad (10)$$

In which t_d is the dressing time (h). Substituting (4) into (10) we have:

$$t_{d,p} = t_d \cdot t_g / t_w \quad (11)$$

$t_{cw,p}$ is the time for changing a grinding wheel per workpiece (h); $t_{cw,p}$ can be calculated as:

$$t_{cw,p} = t_{cw} / n_{p,w} \quad (12)$$

where, t_{cw} is the time for changing a grinding wheel (h).

Substituting (3) into (12) we have:

$$t_{cw,p} = 2t_{cw}\left(\delta_{rs} + a_{ed,ges}\right) / \left[n_{p,d}\left(d_{s,0} - d_{s,e}\right)\right] \quad (13)$$

t_c ***is the grinding time (h); it can be calculated as [22]:***

$$t_c = \frac{l_w \cdot a_{e,tot}}{v_{fa} \cdot v_{fr}} \quad (14)$$

The relationship between the grinding cost and the exchanged grinding wheel diameter (calculated by equation (1) with D_0=25 (mm); B_s=25 (mm); a_{ed}=0.12 (mm); C_{mh}=3 (USD/h); C_{wh}=2 (USD/h); C_{gw}=3 (USD/h); T_w=20 (min.); W_{pd}=0.02 (mm/dress); tg=7; R_{ld}=2) is presented in Figure 1. It is indicated that the grinding cost strongly depends on the exchanged grinding wheel diameter. The minimal value of the grinding cost is obtained when the

exchanged grinding wheel diameter equals an optimum value D_{op}=12.5 (mm) which is much larger than the conventional exchanged grinding wheel diameter (in this case about 8 to 10 mm).

From the above analyses, the optimum exchanged grinding wheel diameter $D_{e,op}$ can be determined by minimizing the manufacturing single cost per piece C_{sin}. Thus, the cost function can be expressed as

$$\min C_{\sin} = f(D_e) \quad (15)$$

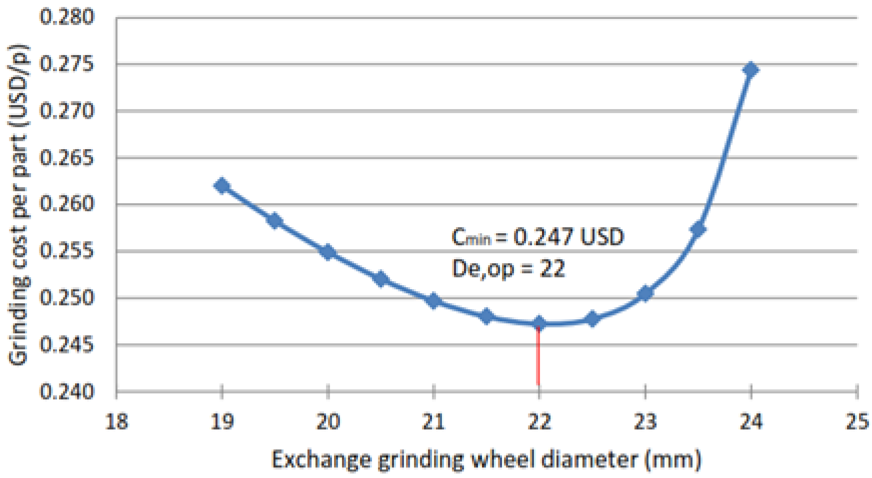

Figure 1 Grinding cost versus exchanged grinding wheel diameter

$$D_{e,\min} \le D_e \le D_{e,\max} \quad (16)$$

In addition, the value of the optimum exchanged grinding wheel diameter depends on various grinding process parameters. Ten grinding parameters including the initial grinding wheel diameter D_0, the width of grinding wheel B_{wg}, the total depth of dressing cut a_{ed}, the tolerance grade tg, the wheel life T_w, the radial grinding wheel wear per dress W_{pd}, the machine tool hourly rate C_{mh}, the wages including overhead cost C_{wh}, the grinding wheel cost C_{gw}, and the ratio of workpiece length per workpiece dimeter R_{ld} are selected to evaluate their effects on the optimum exchanged grinding wheel diameter. Therefore, the optimum exchanged grinding wheel diameter can be presented as:

$$D_{e,op} = f(D_0, B_{wg}, a_{ed}, tg, T_w, W_{pd}, C_{mh}, C_{wh}, C_{gw}, R_{ld}) \quad (17)$$

3. DESIGN OF EXPERIMENT

To study the influences of those parameters on the optimum exchanged grinding wheel diameter, a set of experiments is designed using a 1/8 fraction 2-level factorial design [23]. The values of ten two-level parameters are presented in Table 1. From this kind of experiment design, 2^{10-3} =128 designed experiments are set up as shown in Table 2 with different grinding parameter values. Based on the equations in Section 2, at each experiment, the exchanged grinding wheel diameter is calculated and the optimum grinding wheel diameter is determined and listed in the last column in Table 2.

4. RESULTS AND DISCUSSION

Based on the data reported in Table 2, the influences of the grinding parameters on the optimum exchanged grinding wheel diameter are examined. More specifically, Figure 2

illustrates the main effect of each parameter. It is noticed from the slope angle of each line in the figure that the initial grinding wheel diameter has strong effects on the optimum exchanged grinding wheel diameter D_{op}. This optimum diameter D_{op} also depends on the machine hourly rate C_m and the grinding wheel cost C_d. However, it is independent of the other parameters including the total depth of dressing cut t_{sd}, the wheel life T_d and the radial grinding wheel per dress D_{max}. This is obvious as the line is closely parallel to the mean value of all responses.

Table 1 Grinding parameters for "the experiment"

Parameter	Code	Unit	Low	High
Initial grinding wheel diameter	D_0	mm	10	40
Width of grinding wheel	B_{gw}	mm	8	30
Total depth of dressing cut	a_{ed}	mm	0.05	0.15
Tolerance grade	tg	-	6	8
Wheel life	T_w	min.	2	30
Radial grinding wheel wear per dress	W_{pd}	mm	0.01	0.07
Machine tool hourly rate	C_{mh}	USD/h	2	10
Wages including overhead cost	C_{wh}	USD/h	1.5	6
Grinding wheel cost	C_{gw}	USD/p.	1	10
L/d ratio	R_{ld}	-	1.2	4

Table 2 Experimental Plans and Output Response

StdOrder	RunOrder	CenterPt	Blocks	D0	Bgw	aed	tg	Tw	Wpd	Cmh	Cwh	Cgw	Rld	Dop
118	1	1	1	40	8	0.15	6	30	0.07	10	1.5	10	1.2	27.98
117	2	1	1	10	8	0.15	6	30	0.07	10	6	10	4	5.56
102	3	1	1	40	8	0.15	6	2	0.07	10	1.5	1	1.2	27.67
73	4	1	1	10	8	0.05	8	2	0.01	10	1.5	1	1.2	5.75
94	5	1	1	40	8	0.15	8	30	0.01	10	1.5	1	1.2	34.98
18	6	1	1	40	8	0.05	6	30	0.01	2	1.5	1	1.2	33.79
101	7	1	1	10	8	0.15	6	2	0.07	10	6	1	4	5.34
92	127	1	1	40	30	0.05	8	30	0.01	10	1.5	1	4	36.04
81	128	1	1	10	8	0.05	6	30	0.01	10	1.5	1	4	8.14

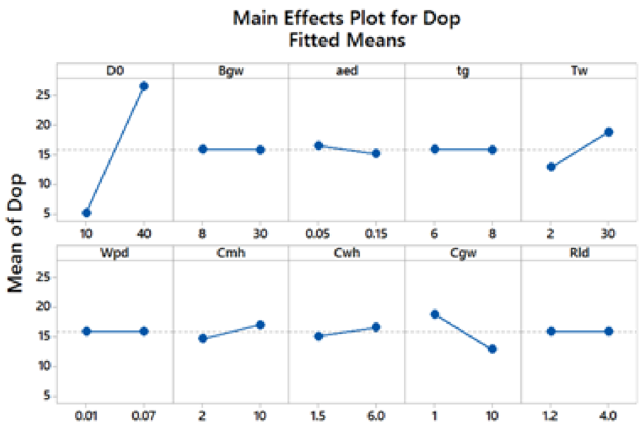

Figure 2 Main effects plot for optimum exchanged grinding wheel diameter

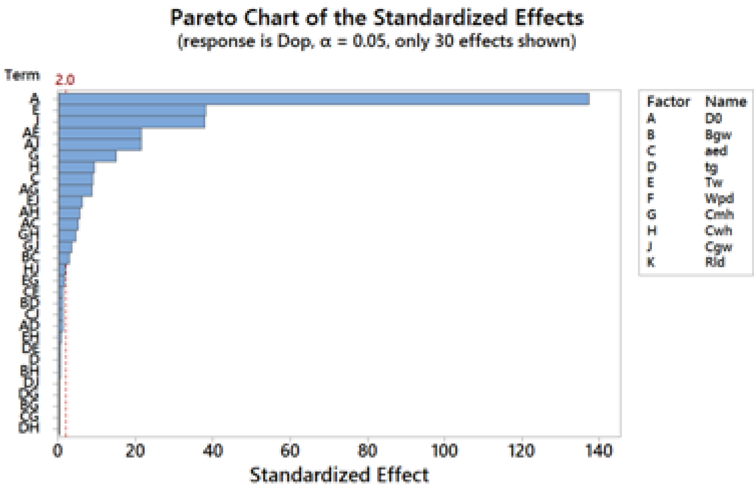

Figure 3 Pareto Chart of the Standardized Effects

The Pareto chart of the standardized effects is demonstrated from the largest to the smallest effect in Figure 3. The largest effect belongs to the initial grinding wheel diameter A. The second largest influence falls onto the wheel life E, etc. Based on the chart display, it can be drawn that those parameters including A (the initial grinding wheel diameter), E (the wheel life), J (the grinding wheel cost), G (the machine hourly rate), H (the wages including overhead cost), C (the total depth of dressing cut), and the interactions AE, AJ, AG, EJ, AH, AC, GH, GJ and BC are statistically significant at the 0.05 level with the response model as their representing bars cross the reference line.

Figure 4 exposes the Norman Plot of the standardized effects, based on which the influences of rising or falling response can be estimated. In addition, the standardized effects are delivered to the majority of parameters close to the reference line (see the red line in Figure 4). Significantly, the nine parameters including the initial grinding wheel diameter D_0, the wheel life T_w, the machine tool hourly rate C_{mh}, the wages including overhead cost C_{wh} and the interactions AE, AG, EJ, AH and GJ have positive influences. When they alter from the low value to the high value, the optimum diameter of the exchanged grinding wheel increases. Contrarily, the other parameters such as the total depth of dressing cut a_{ed}, the grinding wheel cost C_{gw}, and the interactions AJ, AC, GH and BC have negative effects which decline the optimum exchanged grinding wheel diameter. Additionally, the optimum exchanged grinding wheel diameter is predominantly dependent on the initial grinding wheel diameter D_0 since it contains the largest magnitude.

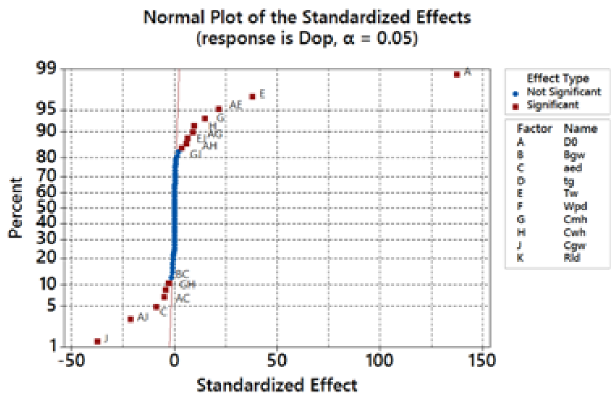

Figure 4 Normal Plot for D_{op}

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		15.7916	0.0686	230.06	0.000	
D0	21.4863	10.7431	0.0686	156.51	0.000	1.00
Bgw	-0.0181	-0.0091	0.0686	-0.13	0.895	1.00
aed	-1.4000	-0.7000	0.0686	-10.20	0.000	1.00
Tw	5.9425	2.9713	0.0686	43.29	0.000	1.00
Cmh	2.3319	1.1659	0.0686	16.99	0.000	1.00
Cwh	1.4519	0.7259	0.0686	10.58	0.000	1.00
Cgw	-5.9087	-2.9544	0.0686	-43.04	0.000	1.00
D0*aed	-0.8131	-0.4066	0.0686	-5.92	0.000	1.00
D0*Tw	3.3744	1.6872	0.0686	24.58	0.000	1.00
D0*Cmh	1.3750	0.6875	0.0686	10.02	0.000	1.00
D0*Cwh	0.8725	0.4362	0.0686	6.36	0.000	1.00
D0*Cgw	-3.3706	-1.6853	0.0686	-24.55	0.000	1.00
Bgw*aed	-0.4575	-0.2288	0.0686	-3.33	0.001	1.00
Tw*Cgw	0.9581	0.4791	0.0686	6.98	0.000	1.00
Cmh*Cwh	-0.7106	-0.3553	0.0686	-5.18	0.000	1.00
Cmh*Cgw	0.5250	0.2625	0.0686	3.82	0.000	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.776592	99.63%	99.58%	99.51%

Figure 5 Estimated Effects and Coefficients for D_{op}

With the elimination of the insignificant effects, Figure 5 displays the estimated effects and the coefficients of D_{op} function. It can be recognized that those parameters including the initial grinding wheel diameter D_o, the total depth of dressing cut a_{ed}, the wheel life T_w, the machine hourly rate C_{mh}, the wages including overhead cost C_{wh}, the grinding wheel cost C_{gw} and the interactions between D_0 and a_{ed}, D_0 and T_w, D_0 and C_{mh}, D_0 and C_{wh}, D_0 and C_{gw}, B_{gw} and a_{ed}, T_w and C_{gw}, C_{mh} and C_{wh} and C_{mh} and C_{gw} have significant effects on a response as their P-values are lower than 0.05. Similarly, B_{gw} has an insinificant effect on the response (D_{op}) since its value of 0.895 is higher than 0.05. Nevertheless, in the interaction with a_{ed}, it significantly influences D_{op} ($p = 0.001$). Thus, to express the relation between the optimum diameter and the significant effect parameters the following equation is introduced.

$$\begin{aligned} D_{op} = & -+0.2364C_{wh} - 0.1198C_{gw} - 0.542D_0 * a_{ed} + 0.008034D_0 * T_w + 0.01146D_0 * C_{mh} \\ & + 0.01293D_0 * C_{wh} - 0.02497D_0 * C_{gw} - 0.416B_{gw} * a_{ed} - 0.03948C_{mh} * C_{wh} \\ & + 0.01458C_{mh} * C_{gw}3.283 + 0.6620D_0 \\ & + 0.0408B_{gw} + 7.45a_{ed} + 0.0114T_w + 0.0729C_{mh} \end{aligned} \quad \textbf{(18)}$$

It is reported from Figure 5 that the adj-R^2 and pred-R^2 have high values, which shows that equation (18) fits the data very well. Thus, it can be used to determine the optimum exchanged grinding wheel diamter when internal grinding stainless steel.

5. CONCLUSION

This study has developed a method to minimize the grinding cost based on determining the optimal determination of exchanged grinding wheel diameter in internal grinding stainless steel 316. Based on the mathematical relations of the grinding cost, the grinding wheel diameter and the grinding process parameters, the effects of ten grinding process parameters on the optimum exchanged diameter have been investigated by designing and conducting a

simulation experiment and analyzing the experiment results afterwards. From the analyzed results, the initial grinding wheel diameter, the machine hourly rate, and the grinding wheel cost have been found to have the strongest effect on the optimum exchanged diameter. In addition, the optimum exchanged diameter is presented as a function of the grinding process parameters and this relation can be further applied for the real grinding experiments.

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